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THE FOLLOWING PAGES ARE CHANGES
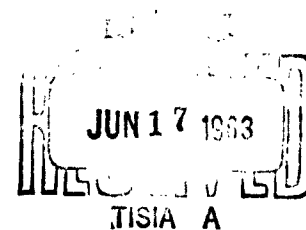
TO BASIC DOCUMENT

ADDENDA
for
Technical Report No. 298

SOME TESTS OF IONIZATION GAUGES
F. T. Worrell

During a further examination of some of the effects described in TR-298, the author has discovered some errors in Figs. 4 and 7. Corrected versions of these figures are reproduced herein. In Figs. 4(a) and (b) a point near the bottom of the graph is now at the top, and some points previously omitted from the prints have been inserted. In Figs. 7(a-c) points inadvertently omitted have been put in, while plotting errors have been corrected in 7(a) and (d). The result of the first change is to bring three related points into a more consistent relationship with one another on all the graphs. These points are enclosed by a curved line in each graph in Figs. 4 and 7. It is now possible to explain tentatively a scatter that was previously unexplainable.

The footnote on page 12 may still be valid, but it should be changed to say that in all cases (omitting "but one") the notably erratic K_o-values were high, since the point that has been corrected was previously the exception. However, another explanation for the scatter suggests itself, and may replace the discussion in the first paragraph on page 12. If we consider the three troublesome points, we note that, ⸴ Fig. 4, the scatter is worst for BA2, almost as bad for N2, less for BA1, and barely noticeable for N1. The relative order in which these effects occur, and the direction of the deviations from the norm are consistent with the Redhead gauge interaction discussed on pages 13−17. Unfortunately, there is no record of disturbances in I⁻ having been noted at these times, so the explanation is speculative.

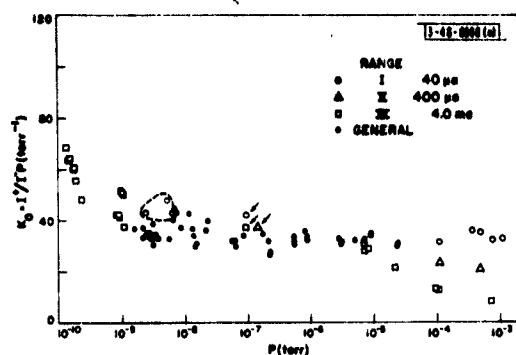In view of this plausible explanation, the removal of these points on the grounds that they are not representative of normal behavior seems justified. If this is done, it will be seen that the remaining plots in Fig. 4, and more especially Fig. 7, are notably improved. In particular, the agreement between N2 and BA2 in Fig. 7(d) is now very good.

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(a) The enclosed Nottingham gauge, N1.

(b) The open Nottingham gauge, N2.

(c) The enclosed Bayard-Alpert gauge, BA1.

(d) The open Bayard-Alpert gauge, BA2.

Fig. 4. Sensitivity of ionization gauges at various pressures.

(a) The two Nottingham gauges, N1 and N2.

(b) The two Bayard-Alpert gauges, BA1 and BA2.

(c) The two enclosed gauges, BA1 and N1.

(d) The two open gauges, BA2 and N2.

Fig. 7. Comparisons of gauges in pairs, range I (40 µa).

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

SOME TESTS OF IONIZATION GAUGES

F. T. WORRELL

Group 48

TECHNICAL REPORT NO. 298

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ABSTRACT

Comparisons are made between ionization gauges of the Bayard-Alpert and Nottingham designs and Redhead's cold-cathode magnetron gauge. Conclusions are drawn about the reliability of each of these under various vacuum conditions. Observations on the effectiveness of the screen in Nottingham's gauge are reported. Miscellaneous effects, such as interactions between gauges, are noted.

LEXINGTON   MASSACHUSETTS

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SOME TESTS OF IONIZATION GAUGES

I.   INTRODUCTION

In recent years, workers in the field of vacuum technology have been looking more critically than formerly at vacuum gauges, in the realization that the gauge does not always tell you what you think it is telling you. Alpert[1] has discussed the question of the reliability of ionization gauges in some detail, with particular reference to the variable sensitivity of the gauges for various gases, and to the errors introduced by the pumping action of the gauges. Blears[2,3] has shown that large errors can be made in measurements in a system containing vapors from an oil-diffusion pump. Carter, et al.,[4,5] have shown that an ionization gauge can operate in each of two different modes that have widely differing sensitivities. Barnes[6] asserts that Bayard-Alpert gauges can produce gases in large enough quantities to cause a cold-cathode monitoring gauge to indicate an increase in pressure by a factor of one hundred, without the test gauge itself showing any indication of the gases. Furthermore, he says that the Bayard-Alpert gauge emitted electrons in large numbers.

In view of discussions such as these, on the one hand, and on the other hand, evidence in some papers that the authors either were not aware of the various results, or disagreed with them, the author decided to make an evaluation of some available gauges under conditions similar to those that might be encountered in the work on oxide cathodes at Lincoln Laboratory. The results were not expected to reveal fundamental information about the gauge parameters, but rather something about the over-all reliability of the gauges under certain conditions. What we have to report here is a collection of observations made in the course of our work, rather than a completed program. Insofar as questions are left unanswered, others may wish to pursue the work further.

Our general plan was to incorporate the test gauges into a conventional high-vacuum system with an oil-diffusion pump and one or two liquid-nitrogen traps, and to operate the system at various pressures from 10^{-3} torr down to the lowest we could attain. We also planned to operate the system for a while without any trapping, after the other tests were made. The gauges compared were: the Bayard-Alpert gauge, Nottingham's modification of the Bayard-Alpert gauge,[7] and the cold-cathode magnetron gauge of Redhead.[8]

A diagram of Nottingham's gauge, as supplied by Ryan, Velluto, and Anderson Glassblowers, of Cambridge, Massachusetts, is shown in Fig. 1. The screen and electron collector are cylinders concentric with the ion collector. Some critical dimensions are given in Table I. The filaments, electron collector, and ion collector are as in the Bayard-Alpert gauge, except that Nottingham has added end caps, consisting of open grids, to the electron collector. The other

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change made by Nottingham is the screen grid added outside the rest of the gauge. The end caps are to prevent the drift of ions out through the ends of the electron-collector grid before they are captured by the ion collector. By their presence, they increase the sensitivity of the gauge and, as a consequence, allow the operation of the gauge to lower pressures before errors from the x-ray effect become serious. The screen, which is held at a negative potential with respect to the filament, is intended to isolate the gauge proper from the walls and to increase the sensitivity somewhat. The Bayard-Alpert gauges in our experiment were made to the same specifications as the Nottingham gauge, with the screen missing. Since we were not concerned with the effects of the end caps of the electron collectors, these were allowed to remain. Our tests, then, showed the effect of the screen.
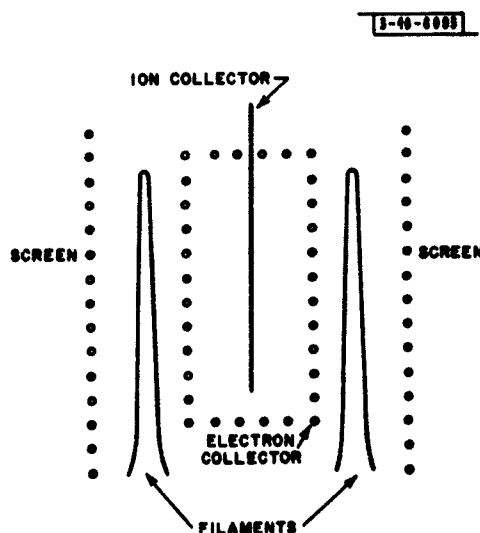

Fig. 1. Nottingham's gauge. The screen and electron collector are cylinders concentric with the ion collector.

TABLE I			
IONIZATION GAUGE DIMENSIONS			
	Electron Collector	Screen	Ion Collector
Diameter (in.)	1.0	1.75	0.003
Length (in.)	1.5	1.75	—

II. EXPERIMENTAL METHOD

The ionization gauges and the magnetron gauge were mounted in a symmetrical array on a spherical bulb 20 cm in diameter, with the magnetron gauge opposite to the pumping line, and the others symmetrically arranged about it. The arrangement is shown in Fig. 2, which is a view from the rear, i.e., the side away from the pumping line. The circles represent the locations of the gauges: the Redhead gauge (R), the Nottingham gauges (N1 and N2) and the Bayard-Alpert gauges (BA1 and BA2). Two of the ionization gauges, N2 and BA2, are "open," i.e., mounted directly in the spherical chamber, as indicated schematically in sketch (a) at the lower left in Fig. 2, and so positioned that neither could "see" directly down the pumping line. (It should be noted, however, that the two gauges could "look" at each other, in spite of the screen on N2, since this screen is open at the end. An effect resulting from this condition will be discussed later.) The other two gauges, N1 and BA1, are enclosed in their own envelopes, and each is connected to the spherical chamber by a tube 2.2 cm in diameter and 10 cm long, of conductance 10 l/s, as shown schematically in sketch (b) at the lower right in Fig. 2. By this arrangement, we are able to compare: (a) identical gauges (e.g., N1 and N2) in different environments, (b) different gauges (e.g., N1 and BA1) in similar environments, and (c) any of these to the magnetron gauge.

In addition to the test gauges, attached to the chamber were three lines leading to an omegatron, a McLeod gauge, and a source of pure nitrogen, respectively. Granville-Phillips metal valves were used for V_1, V_2, and V_3. When the McLeod gauge was not being used for measurement, it was isolated from the system by closing V_4.

The vacuum chamber was evacuated by a 25 l/s oil-diffusion pump with two liquid-nitrogen cold traps in series, as shown in Fig. 3. The trap nearer to the vacuum chamber was above the table top, and hence bakeable; the other trap was below the table. Actually, except when the lowest pressures ($<10^{-9}$ torr) were desired, only the lower trap was needed. Attached to the pumping line below the table was a Veeco Vacuum Corporation (New Hyde Park, New York) TG-75 gauge (V), which served as a monitor at all times.

The four ionization gauges were run off laboratory power supplies whose circuit is shown in the Appendix (Fig. A-1). Each supply provided a stabilized electron current (I^-) adjustable from 20 µa to 5 ma in three ranges selected by a rotary switch. On the basis of an earlier rough calibration of this type of gauge, we operated the gauges at electron currents (measured at the electron collector) of 40 and 400 µa, and 4.0 ma, referred to hereafter as ranges I, II, and III, respectively. At these currents the ratio of positive-ion current to pressure (I^+/P) had the approximate values of 10^{-3}, 10^{-2}, and 10^{-1} amp/torr, respectively. A second selector switch (SW$_2$) allowed the gauge to be put in a "standby" condition on any of the ranges. In the standby condition the electron-collector voltage is off, and the filament is maintained at normal operating temperature by an auxiliary circuit.

The meter M_2 indicates filament voltage. Since the electron current is stabilized, changes in this voltage reflect adjustment to changed vacuum conditions. For example, in one test where the vacuum system started at a pressure around 10^{-9} torr with the trap refrigerated and ended at 2×10^{-7} torr with the trap warm, the filament voltage for one gauge went from 4.2 to 6.2 volts. This represents the extreme variation that would be expected. The electron-collector voltage was stabilized at +108 volts with respect to the filament, which in turn was between 25 and 30 volts above ground, depending on the electron current being drawn. The screen, if any, was grounded, and therefore varied between 25 and 30 volts below filament, a variation which has
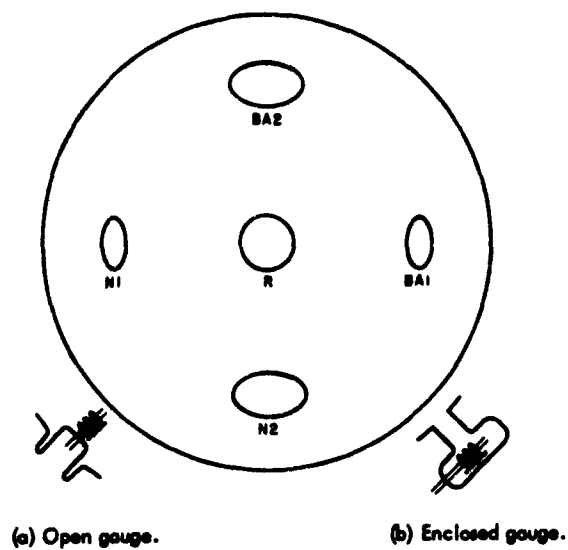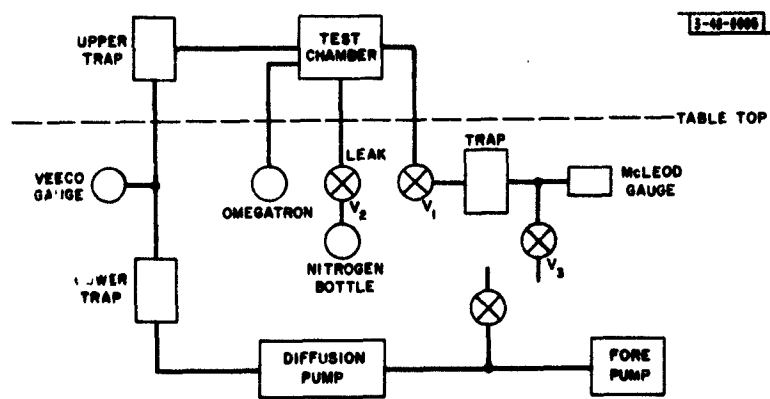
(a) Open gauge.   (b) Enclosed gauge.

Fig. 2. Arrangement of the gauges.

Fig. 3. Layout of vacuum system.

been found to have a negligible effect on the positive-ion current (I^+) at the ion collector. The ion collector was grounded through the input resistance of a Keithley Instruments (Cleveland, Ohio) Model 410 micro-microammeter.

The procedure for pumping down the chamber, designed to minimize the chance of contamination by oil vapors, was:

(a) The system was pumped down by the forepump to a few microns.

(b) The part of the system above the table top was heated to 150°C, while the part below the table was torched, starting from the part nearest the vacuum chamber and going to the diffusion pump.

(c) The lower trap was refrigerated.

(d) The diffusion pump was turned on.

(e) When the diffusion pump had taken hold, the high-temperature bake of the upper part of the system was started.

(f) When the system was near the end of the baking period but still at the baking temperature, degassing of the ionization gauges was started. This degassing was continued after the oven was shut off, until the system was at room temperature.

(g) While the vacuum chamber was being baked, the omegatron was heated by a heating tape for several hours, cooled, and the metal parts heated by rf induction heating.

The initial bakeout period was for about 45 hours, of which 12 were at 350°C and the remainder at 400° to 425°C. In the middle of this period, the ionization gauges were degassed, the omegatron was baked at 400°C for several hours and its metal parts degassed. At the end of the bakeout, the gauges were again degassed as in (f). After some preliminary tests, the system was baked over a weekend, some 49 hours, at 350°C.

In the middle of the subsequent group of tests, the appearance of argon and oxygen in the omegatron spectrum, and a rise in total pressure to 3×10^{-7} torr, indicated an air leak, which was found in the stem of an ionisation g   Since it was not practicable to repair this at the time, the leak was plugged with glyptal   leak indications disappeared quickly, and we were eventually able to achieve pressures at $< 10^{-10}$ torr under these conditions.

The gauges were calibrated against   r leed gauge in the range 10^{-5} to 10^{-3} torr by admitting pure nitrogen into the system that   he variable leak and taking readings when a steady state was achieved at each leak setting   such runs, each up and down in pressure, taken on different days, produced a consistent set of points. Because of the usual difficulties in obtaining accurate readings on the McLeod gauge in this pressure range, the readings are not highly accurate, but are sufficient for our present purposes. To say that the points were consistent we mean that, when the estimated error in each point was taken into account, it was possible to draw a straight line, or other smooth curve, through the points. The errors in reading the McLeod gauge, estimated from the variability of repeated settings at the same pressure, varied from ±5 percent at 10^{-3} torr to ±35 percent at 7×10^{-6} torr, the lowest pressure at which we attempted to use the McLeod gauge. Our estimates may have been pessimistic, since the graphs which we shall present later show less scatter than we should expect from these estimates. In any event, our interest was not primarily in establishing a precise calibration of our gauges, so it was not essential that we improve the techniques with the McLeod gauge.

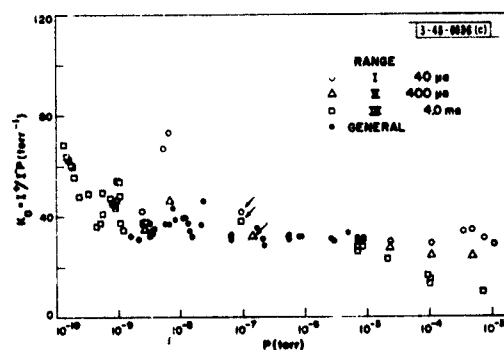After the calibration runs against the McLeod gauge were made, the pressure in the system was run up several times by leaking nitrogen into the chamber, and then run down, and readings
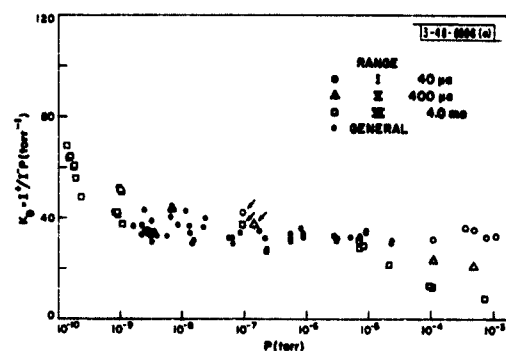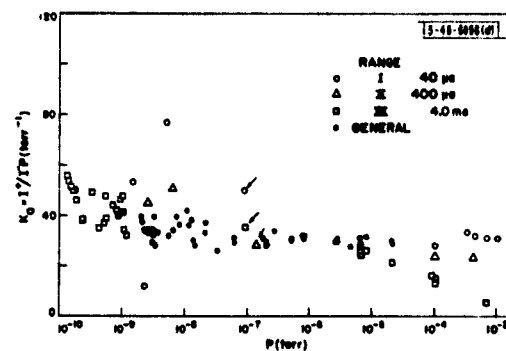
(a) The enclosed Nottingham gauge, N1.
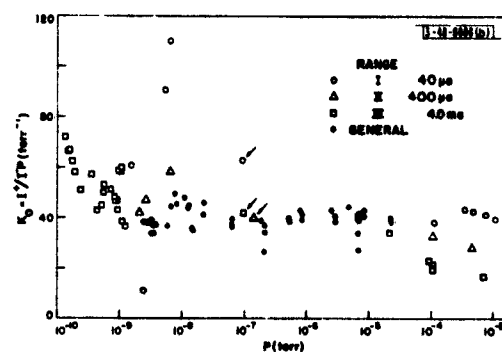
(b) The open Nottingham gauge, N2.

(c) The enclosed Bayard-Alpert gauge, BA1.

(d) The open Bayard-Alpert gauge, BA2.

Fig. 4. Sensitivity of ionization gauges at various pressures.

taken on all the gauges at various pressures. In addition to reading the gauges, we performed some other tests, as we shall describe later. To achieve the lowest pressures, the upper trap was refrigerated.

III. RESULTS

The measurements have been analyzed in two different ways, first by comparing each of the ionization gauges to a reference gauge, and second, by intercomparing the ionization gauges in various ways. Figures 4(a-d) present graphs of the gauge constant, $K_o = I^+/I^- P$, for each ionization gauge vs pressure. "Pressure" in this case means the reading of the McLeod gauge for pressures from 7×10^{-6} torr up, and the reading of the Redhead gauge for lower pressures. The justification for using the latter gauge as a reference is that, in the first place, its indication agreed with that of the McLeod gauge in the small range in which their scales overlapped; in the second place, by using its indication in calculating K_o for the ionization gauges we find that K_o remains constant for about three decades below the changeover point; and finally, even if its linearity may not have been demonstrated here, the results are consistent with a linearity assumption. The second method of analysis results in the graphs of Figs. 5 through 7, in which are plotted the ratios of positive-ion currents for two of the gauges vs pressure as defined above. Figures 5(a-d) are plots showing the variations of the ratios with pressure on range III (4.0 ma). Figures 6 and 7 deal with ranges II (400 μa) and I (40 μa), respectively. For each range, in (a) and (b) are plotted the variations I^+_{N1}/I^+_{N2} and I^+_{BA1}/I^+_{BA2}, respectively, representing comparisons between like gauges in different environments. The other plots compare unlike gauges in the same environment.

In no case is the absolute value of one of these ratios of concern, but only the change in ratio. From this viewpoint, neither the calibration of the individual gauges nor the accuracy of our pressure scale is of great concern. If the pressure scale is not accurate, and the related function is not varying linearly with pressure, no essential change is seen in the plot; if the ratio function is changing, the effect of, say, a compression of the pressure scale at one end is to exaggerate the rate of change of the function. This distortion will be the same for all the plots, however, so comparisons can still be made.

In the graphs of K_o vs P (Fig. 4) most of the points are represented by dots. Where the range (I, II, or III) at which the reading was taken was of interest, the special symbols shown in the legend were used. We shall comment at this point only on the systematic features appearing at the pressure extremes. At the high-pressure end we see the expected result that on ranges II and III the gauges deviate from linearity, while on range I the behavior is quite good out to 10^{-3} torr. The hump in the range I plot, of which there is a suspicion in the range II plot, is believed to be the result of an error in the McLeod gauge readings. At the low-pressure end, K_o rises with decreasing pressure. This rise is consistent from one gauge to the other, as can be seen from the constancy of the various intercomparison ratios in Figs. 5-7, at these same pressures. Leakage currents are ruled out, first because it would require much larger ones than have been found by other means, and second because they would not be uniform from one gauge to the other. If we assume the rise to come from the x-ray effect, the x-ray limit would be around the middle of the 10^{-11}-torr range, which is normal for gauges of this design. The agreement with the results of others in this case gives a rough indication that the Redhead gauge is continuing to behave well at these low pressures, i.e., that it is providing a valid pressure scale.
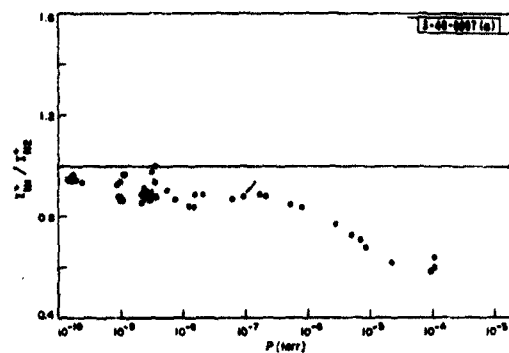
(a) The two Nottingham gauges, N1 and N2.
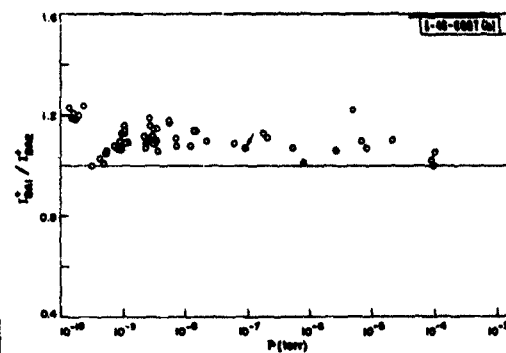
(b) The two Bayard-Alpert gauges, BA1 and BA2.
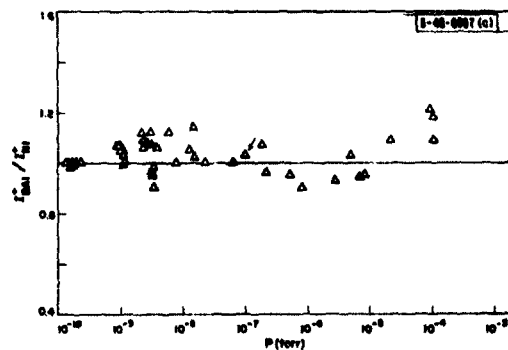
(c) The two enclosed gauges, BA1 and N1.

(d) The two open gauges, BA2 and N2.

Fig. 5. Comparisons of gauges in pairs, range III (4.0 ma).

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(e) The two Nottingham gauges, N1 and N2.

(b) The two Bayard-Alpert gauges, BA1 and BA2.

(c) The two enclosed gauges, BA1 and N1.

(d) The two open gauges, BA2 and N2.

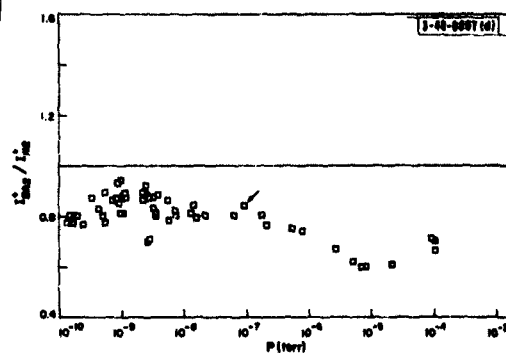Fig. 6. Comparisons of gauges in pairs, range II (400 μs).
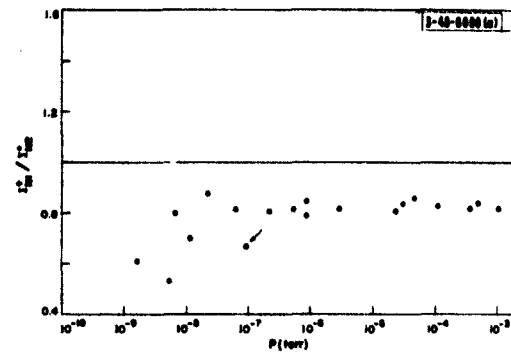
(a) The two Nottingham gauges, N1 and N2.
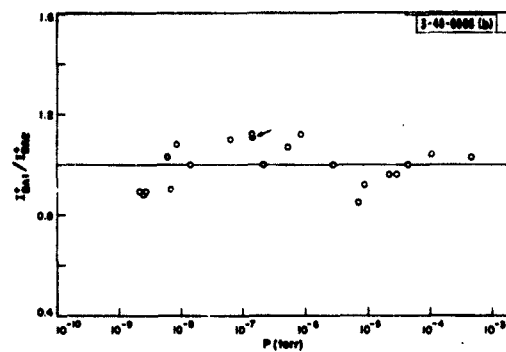
(b) The two Bayard–Alpert gauges, BA1 and BA2.

(c) The two enclosed gauges, BA1 and N1.

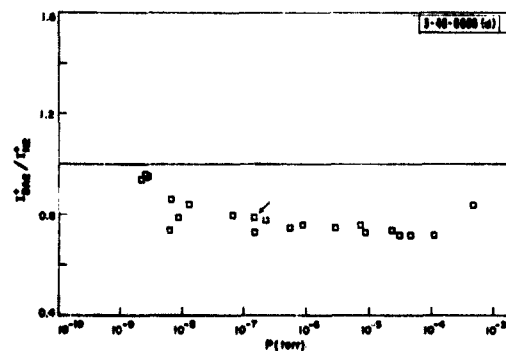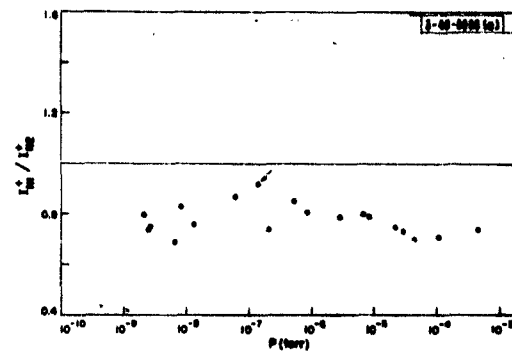(d) The two open gauges, BA2 and N2.
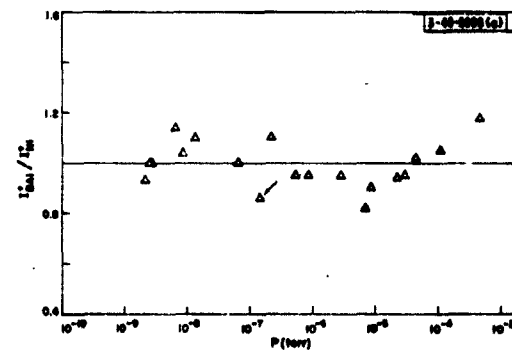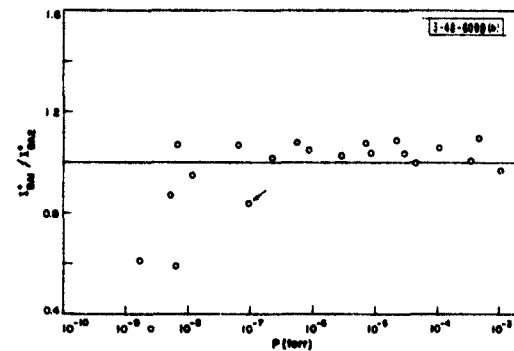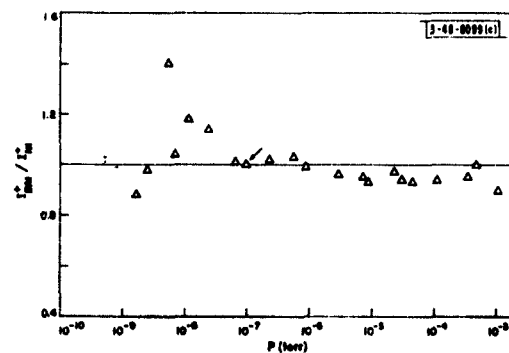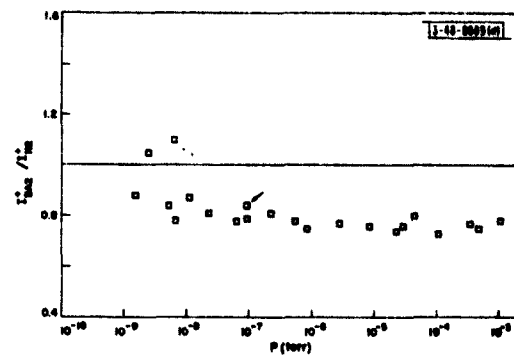
Fig. 7.   Comparisons of gauges in pairs, range I (40 μa).

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Figure 5(a), comparing N1 and N2 on range III ($I^- = 4$ ma), shows fairly low scatter of the points, but a large and steady drop in the ratio at high pressures. Figure 5(d), comparing BA2 and N2, is similar. Figure 5(b) shows no drop, while there appears to be a rise in 5(c). Looking back at Fig. 4, we see that N2 departs less from linearity than do the others. However, these variations between gauges are more evident in the ratio plots. There seems to be no simple explanation of these variations. We should expect to find that (a) the two open gauges are consistent, (b) the two Nottingham gauges are consistent, or (c) a combination of (a) and (b) which results in the enclosed Bayard-Alpert gauge tracking relatively poorly with the others. None of these assumptions seems to work.

On the matter of the scatter of the points, the indications are clearer. There is notably less scatter in the graphs relating N1 to N2 and BA2 to N2 than in the others. Since the scatter probably represents the effects of local fluctuations in the environment, it would appear from the small scatter for the first ratio that the Nottingham gauge is less sensitive to local fluctuations in the environment, i.e., will give a more reliable reading under varying conditions; from the small scatter in the second ratio, we see that either type of gauge is equally good in the open position. Neither result is unexpected, since we should expect that the grounded screen of the Nottingham gauge would provide some isolation from wall effects, whereas in the open position the wall effects are much reduced. The wall effects might be expected to affect the linearity of the calibration, but if they do there must be some compensating effect which produces the results we have shown.

The corresponding graphs for ranges II and I ($I^- = 400$ and 40 μa) are shown in Figs. 6 and 7, respectively. At the lower electron currents the agreement of the gauges with one another in the high-pressure region is better. These results are in agreement with our earlier observation that the gauges are more linear at lower electron currents. We also see that the scatter of the readings is somewhat less on range I than on range III, except at the low-pressure end of the graphs, where the scatter is bad. In spite of the scatter, we can still see that the ratios I_{N1}^+/I_{N2}^+ and I_{BA1}^+/I_{BA2}^+ still drop appreciably as the pressure goes down, whereas the other two rise. There is no obvious explanation for the second effect. The first, which involves ratios of ion currents of enclosed-to-open gauges, we are tempted to ascribe to the pumping action of the gauges. This cannot be the cause, since the relative depression in the pressure in the enclosed gauge, and hence in the positive-ion current produced by the gauge, should be independent of pressure if the pumping speed is constant, as is usually assumed. (Hobson,[9] in his study of the pumping action of Bayard-Alpert gauges presents results that indicate that the pumping speed is not linearly related to the electron current, and is independent of pressure.) In any case, when one calculates the expected pressure drop across the connecting tube to an enclosed gauge, using published values of pumping speed,[9] he obtains figures of the order of a few percent, which are much smaller than the changes seen in these graphs.

If we look at the graphs of all four ratios, we find that it is impossible to assume that only two of the gauges were varying. It is more likely that all four were varying to a greater or lesser degree. It is notable that the ratio I_{BA2}^+/I_{N2}^+ fluctuated less than the others, not only at low pressures, but at all pressures and on all ranges. This confirms the expectation that either gauge is equally good in the open position. We also see that the relatively good agreement (in terms of low scatter of points) between N1 and N2 noted earlier for range III continues on ranges II and I.

The large scatter in range I readings at low pressures is also evident in Fig. 4. The scatter is worst for N2 and BA2, less for BA1, and absent from the N1 plot. If we assume that the enclosed gauges (N1, BA1, and R) are more likely than the others to read incorrectly because of local outgassing, we should expect to find small scatter in the ratio plot for N2 and BA2, and larger scatter in the K_o plots, as we do. Why the K_o plot for N1 should show such small scatter, however, is not clear.

In this work it was apparent that adequate degassing was not only important, but difficult to obtain. However, it was not evident from readings of a single gauge when outgassing was a serious factor. All the readings shown were presumably steady-state readings. In the later part of the experiment the gauge readings were recorded continuously, and the records were inspected before deciding that a steady state existed. Yet there was a serious scatter in some readings, especially those taken when the pressure was first run down into a lower range. The inadequacy of the steady-reading criterion showed up when we examined the readings more carefully. For one thing, a tendency for I^+ to change by a factor greater than that by which I^- changed when we switched from one range to the next was sometimes indicative of outgassing. This was not a certain criterion, however, since this same effect showed up in several readings taken when the system was being operated on a leak at pressures at least one order of magnitude greater than those at which the system had been operated earlier. A more certain indication of outgassing was that later readings in the same pressure range fitted with surrounding readings quite well, disagreeing with the earlier scattered readings. By applying these criteria and some hindsight about techniques, we were able to eliminate several scattered readings in this way. Those that remain have not been explained in any satisfactory way.*

As a conclusion to the series of measurements, the cold trap was allowed to warm up to room temperature. The pressure rose to about 1×10^{-7} torr. The gauges were read on each range in turn, in each case following a period of stabilizing at that operating condition for at least 8 hours. The readings for this condition are marked by arrows in Figs. 4-7. The only place where the points deviate significantly from the others is on range I, in the ratios comparing an enclosed to an open gauge. The ratio is low for both gauges. It is also of interest to note that, in the graphs comparing each ionization gauge to the Redhead gauge (Fig. 4), the corresponding points for N1 and BA1 are in line, but those for N2 and BA2 are high. We might be inclined to blame this effect on the pumping action of the enclosed gauges (N1, BA1, and R), resulting in lower pressures in them. This is clearly not so, however, since on ranges II and III the effect should be either worse if the pumping is electronic, or as bad if the pumping is chemical. The effect is, as a matter of fact, absent at the higher electron currents.

The absence of any Blears effect (a low reading in the enclosed gauge in the presence of pump oil vapors, resulting from the pumping action of the gauges) in this case was at first puzzling. Two explanations which come to mind are: (a) the gauges were saturated by this time, and not pumping at all, or (b) the conductance of the lines to our enclosed gauges was high enough (10 l/s) that a negligible pressure drop existed along them, even under these severe conditions.

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*Redhead, in a note to be published in <u>Vacuum</u>, has reported an effect of this sort, which he shows to be the result of a jump by a factor greater than one hundred in the x-ray emission, as the result of adsorbed layers of certain gases on the electron collector. The effect disappears after proper outgassing. Our observations that (a) this effect occurred in the early stages of the experiment, and (b) in all cases but one the notably erratic K_o-values were high, are consistent with his explanation.

Blears[2] states that the conductance to his enclosed gauge was 0.7 l/s in his first experiment. If he used the same arrangement in his later work,[3] we can estimate how large an effect he would have seen for a 10 l/s conductance. For his conductance of 0.7 l/s, P_2/P_1, the ratio of the readings of the two gauges, was 0.091. If we calculate by a direct proportion, and ignore the effects of the change in this conductance on other parameters in the system, we find, for a 10 l/s conductance $P_2/P_1 = 0.93$, which would result in a rather small Blears effect. On this count alone, without concern for the question of the saturation of our gauges, we can see why the Blears effect was not noted here. This is also consistent with a preliminary experiment of ours[10] in which BA1 was a commercial gauge connected through a somewhat smaller conductance to the main chamber. In that case the gauge reading, relative to that of N2, decreased to 30 percent of its value for a clean system.

It is of interest to note that the scatter in the points on the graphs of Fig. 4 is about ±25 percent, excluding the erratic readings which we have discussed earlier, whereas on the graphs intercomparing the ionization gauges the scatter is only about ±10 percent, an indication that the Redhead gauge is not as stable in operation as the ionization gauges.

IV. MISCELLANEOUS EFFECTS

A. Behavior of the Redhead Gauge

During the course of the experiments, records were taken of the output of the Redhead gauge. These records showed that two types of instability exist. The first, a sort of jitter, is illustrated on the right side of Fig. 8. This jitter may have been associated with a gassy condition in the gauge, because it tended to disappear in the later stages of operation. Figure 9 shows a bad case of the jitters during the warming of the upper trap after a low-pressure run had been made. (The steps have no significance here.) A curious feature of the first figure is that the jumps all take place in the downward direction. If these were the result of gas bursts in the gauge, they should be upward. They may represent attempts to jump into another mode of operation, and hence be related to the second instability, which shows in the big drop, amounting to about 35 percent, on the left in Fig. 8. This is believed to be a jump into another mode.[11] These jumps have been found to last anywhere from a few minutes to several hours. They are large enough to cause serious errors if readings are taken without the aid of a recorder to monitor the behavior. We are in agreement with Torney[11] that this mode jump seems to be restricted to a rather small range in the low 10^{-9}-torr region, a circumstance which makes the effect less serious than it might be if it occurred over a larger range. An interesting feature of this mode jump is that in the second mode there is no jitter. This was invariably the case.

The third effect is apparently the consequence of the design of our Redhead gauge,[*] which makes it impossible to degas it by rf induction heating. The effect in question showed up in the early part of the experiments, and only that one time. The ionization gauges were operating on range II ($I^- = 400 \mu a$). When the Redhead gauge was turned on, the ionization gauges were disturbed in such a way that new stable electron currents were found: $I_{N1}^- = 380 \mu a$, $I_{N2}^- = 200 \mu a$, $I_{BA1}^- = 190 \mu a$, and $I_{BA2}^- \doteq 0$. When the Redhead gauge was turned off, all gauges returned to normal. During the disturbed period, the positive-ion currents in the ion gauges were also disturbed, but not in any systematic way: in the first three gauges the positive-ion current increased

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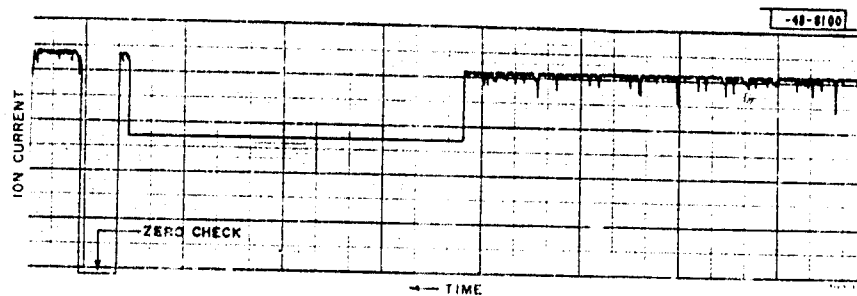[*] Manufactured by NRC Equipment Corporation, Newton, Massachusetts.

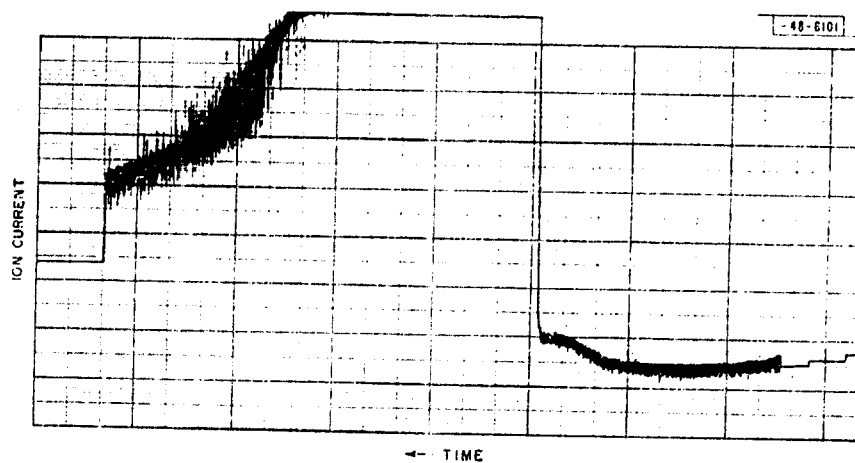Fig. 8.   Instability and mode jump in Redhead gauge.

Fig. 9.   Severe instability in the Redhead gauge after a large pressure surge.

by a factor of about 2 and in BA2 it decreased to about 40 percent of the normal value. This effect was noticed shortly after the Redhead gauge had given evidence of outgassing, i.e., readings were jumpy, and higher than normal relative to the Veeco gauge.

It can be shown that this effect could result from the emission of positive ions by the Redhead gauge, in the following manner. Figure 10 shows a simplified schematic of the emission-regulating circuit for each ionization gauge. Normally the electron current (I^-) will be in the direction shown. It produces a voltage across R_1 which provides the regulation. If positive ions come into the vicinity of the gauge, a few may reach the ion collector, though it is quite well shielded by the electron collector, and cause the disturbances in I^+ which we have noted. But in the case of a Bayard-Alpert gauge, which has no screen, the likely target for the ions is the filament, which is more exposed and at almost as low a potential as the ion collector. This will cause a current (i^+) in the regulating circuit to ground, as shown. Since i^+ to the right produces the same sign of voltage across R_1 as I^- to the left, the voltage across R_1 increases, the regulator compensates by reducing the filament temperature, and I^- drops, as we observed. Some ions reached the filaments of N1 and N2, presumably because the filament supports are not shielded by the screen.

Fig. 10. Simplified schematic of circuit for regulating I^-.
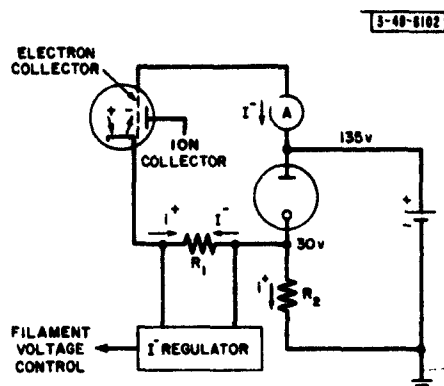
Now, it is interesting to note the relative magnitudes of the effects of the supposed positive ions on the various gauges. Note that N1 is affected less than N2, BA1 less than BA2, N1 less than BA1, and N2 less than BA2. The first two comparisons, between like gauges, show the isolating effect of the separate enclosures. The third and fourth comparisons, between unlike gauges, show that the grounded screen of the Nottingham gauge traps a good many, but not all, of the ions.

If our analysis of the preceding section is correct, it seems to be in disagreement with the conclusions of Barnes.[6] Barnes observed that: (1) when a Bayard-Alpert gauge in his system was turned off, the pressure indication of the cold-cathode gauge used to monitor the pressure dropped by a factor which ranged from eight to one hundred, the magnitude depending on the extent of the previous baking, outgassing, etc.; (2) a rise of about the same magnitude in the indication of the monitor gauge could be produced by heating the wall of the Bayard-Alpert gauge while it was not operating; and (3) after the Bayard-Alpert gauge was turned on, during the period in which the walls were warming up, the cold-cathode monitor gauge indicated a large

TABLE II				
ELECTRON CURRENTS ON RANGE I, ONE FILAMENT ON AT A TIME				
Filament On	I^- (µa)			
	N1	N2	BA1	BA2
N1	40	–	–	–
N2	–	36	–	–
BA1	–	–	40	–
BA2	–	4	–	40
All	40	40	40	40

TABLE III		
TO SHOW ORIGIN OF VARIATIONS IN I^-_{N2}		
Condition	I^-_{N2} (µa)	V (volts)
All filaments on	40	3.0
BA2 filament off	36	3.0
Only BA2 filament on	4	0.0

increase in pressure, whereas the Bayard-Alpert gauge indicated essentially no change.[*] As an explanation of these and other effects, he proposed that positive ions were produced in large numbers in the Bayard-Alpert gauge; and since they were unable to go anywhere but out of the gauge, they did so, thereby producing the large pressure increases observed elsewhere, without their presence having been indicated by the source gauge. This conclusion seems to be contradicted by our experience. Positive ions, produced externally in this case, were apparently picked up by the filaments of our gauges. The gauges used by Barnes had their filaments at ground potential, so one would think that they could quite readily drain off a positive space charge which formed in the region between the electron collector and the gauge wall. Then there would seem to be no reason why the neutral atoms, i.e., neutralized ions, in this region should not diffuse throughout the gauge and be detected in the normal manner.

We mentioned earlier that, accompanying the changes in electron current which result from turning on the Redhead gauge, there were changes in positive-ion current, but not in proportion to the changes in the electron current. In three of the gauges the ion current actually increased and in the fourth (BA2), while the electron current was apparently zero, the positive-ion current was about 40 percent of its undisturbed value. It seems likely that a few positive ions penetrated the electron collector to reach the ion collector. Since the positive-ion currents to the ion collector were of the order of 10^{-10} amp, and the presumed positive-ion currents to the filament were of the order of 10^{-4} amp, it would take only a very few ions leaking through the electron collector to produce the observed effects on the ion-collector current. It is not possible, however, to proceed beyond this speculation.

B. Interactions of Ionization Gauges

On one occasion we observed a small interaction between the two open gauges (N2 and BA2) which could be accounted for by assuming that electrons from one gauge were being picked up by the electron collector of the other. No evident correlation could be found with other conditions, and the effect soon disappeared. The experiments on this effect are discussed below.

(1) All gauge power supplies were set on range I. Each electron current was adjusted to 40 μa while all gauges were running. All four filaments were then turned off, leaving the electrode voltages on. Each filament, in turn, was operated by itself, and I^- read on all the power supplies. The results are shown in Table II. It would appear that BA2 was sending a 4-μa electron current to the electron collector of N2. It was clearly not a positive-ion current to the filament, since this would not have registered on the meter, but would have been bypassed to ground. The preference for electrons to go from BA2 to N2 may be explained by the lack of a screen on BA2, which allows some of the electrons to wander away and be captured by the exposed end of the electron collector of N2.

(2) A voltmeter (R = 800 kohm) was connected in parallel with R_{10} (110 kohm) in the power supply for N2. (This is part of the resistance across which the control voltage developed by I^- appears.) Three of the previous readings were repeated, with the results shown in Table III. If all the electron current that registered on the meter in the power supply went through R_{10} in every case, the respective voltage readings should have been 3.0, 2.7, and 0.3. They clearly

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were not. The 4-μa current apparently was bypassed to ground. This shows it is from an external source, i.e., BA2.

(3) The first test was repeated, with the difference that the source gauge was on range III (filament hotter, more electrons available), while the passive gauges were on range I. The results are presented in Table IV. In the first place, the effect of BA2 on N2 is relatively smaller than before, though absolutely larger. Why the transfer should be less efficient now is not clear. Second, there is now an effect of N2 on BA2.

TABLE IV				
ELECTRON CURRENTS, SOURCE GAUGE ON RANGE III, OTHERS ON RANGE I				
Filament On	I^-			
	N1	N2	BA1	BA2
N1	4.0 ma	—	—	—
N2	—	4.0 ma	—	20 μa
BA1	—	—	4.0 ma	—
BA2	—	31 μa	—	4.0 ma

From the absence of any action on or by the enclosed gauges, it would seem that this interaction depends on the passive gauge's producing an appreciable accelerating field for the electrons near the source gauge. Our effect must be considerably smaller than that reported by Barnes, who worked with enclosed gauges.

C. Action of the Screen of the Nottingham Gauge

Some observations on the effect of the screen of the Nottingham gauge are of interest. The records of positive-ion current taken during the experiment are consistently steadier for the Nottingham gauges than for the Bayard-Alpert gauges. Tests indicated that the fluctuations were "noise," rather than an indication of actual gas bursts. The only two evident external sources are line-voltage fluctuations and electromagnetic disturbances in the vicinity of the gauges. The former are ruled out, because all the gauges were run from identical power supplies off the same Sola constant-voltage transformer, leaving the latter as the most likely source. If this is so, our observation indicates that the screen is an effective shield against such disturbances, as we should expect it to be.

In discussing his gauge, Nottingham[7] says that by adding to a Bayard-Alpert gauge an external screen at a negative potential (with respect to filament) one should be able to increase the sensitivity of the gauge. He does not say how large this increase should be. We were unable to test this assertion by, say, comparing I^+_{N1} to I^+_{BA1}, since, among other things, we could not be sure if the two gauges would have the same intrinsic sensitivity independent of the effect of the screen, i.e., whether N1 with its screen removed would agree with BA1. However, in an attempt to make a Nottingham gauge look somewhat like a Bayard-Alpert gauge, we connected the screen to filament, i.e., +30 volts, instead of the usual ground. Under these conditions the screen

would have less effect on the electrons and ions than when it was grounded, and would allow them freer access to the gauge wall. We tested N1 and N2 in this way, switching the screen from ground to filament to ground again, and noting I^+ in each case. At a pressure around 3×10^{-9} torr, on ranges III and II, we found the sensitivity of N1 to be increased by about 15 percent with the screen grounded (negative with respect to filament) over what it was with the screen at filament potential, while the sensitivity of N2 was unaffected by the same changes in its screen potential. This result would imply that the screen does not in itself basically improve the electron trajectories, but counteracts the deleterious effects of the gauge-wall potential on the trajectories. We have found, in agreement with Carter,[4] that the gauge wall assumes a potential close to that of the filament. It is reasonable to expect that the screen should be beneficial in this situation. Since the open gauge has no wall problem, no benefit in sensitivity is seen for this gauge.

D. Wall Potentials

The matter of wall potential has been investigated by several workers. Cobic, Carter, and Leck[5] assert that, for the conditions under which our gauges operate, the wall should be "at cathode potential." Ehrlich[12] gives figures of +23.2 volts (with respect to ground) at $I^- = 500 \, \mu a$ and a very low pressure (apparently in the low 10^{-10} torr range), and +26.3 volts at a high pressure (about 10^{-4} torr). Referred to the filament, these voltages are -1.8 and $+1.3$ volts, respectively, more or less in agreement with the others. Cobic, et al., measured the wall potential by using a capacitance probe, whereas Ehrlich had a tin-oxide coating on the inside of the envelope.

We have made measurements on a Bayard-Alpert gauge, using Ehrlich's technique. Potentials were measured with a simple potentiometer, as shown in Fig. 11. The potentiometer was adjusted until the current indicated by the Model 600-A was less than 1×10^{-12} A. Repeated adjustments from above and below balance produced voltage readings which varied by less than 0.05 volt. These readings are shown as V_p in Table V. By switching the electrometer to the voltage scale, and setting the potentiometer to zero, we obtained the readings V'_p, which are seen to be in agreement with the others. Considering differences in measuring techniques, different electrode voltages, and the different tube geometries, our readings are surprisingly close to Ehrlich's.

We have also made wall-potential readings on a Nottingham gauge, by the same technique. The results are shown in the last two columns of Table V. The wall potentials differ, though not greatly, from those of the Bayard-Alpert gauge. The significance of the difference is not known. It is of interest to note that wall potential is almost independent of I^- in the Nottingham gauge.

As part of these tests, after each determination of V_p the potentiometer was thrown slightly off balance, always by the same amount in terms of voltage. The Bayard-Alpert gauge showed an unbalance current two to four times that on the Nottingham gauge, indicating that the screen has a retarding effect on the motion of charge to the wall.

Ehrlich[12] shows a graph which indicates that the gauge sensitivity is influenced notably by the potential of the gauge envelope, a change of wall potential from zero to -25 volts (with respect to filament) producing an increase of 25 percent in sensitivity. His gauge was operated at $I^- = 500 \, \mu a$. We have measured this effect on all three of our ranges, and as one can see in Fig. 12(a), the effect is not so great in our case. Over the same range of plate voltages, our sensitivity varies by about 10 percent. In these measurements, a Bayard-Alpert gauge and a
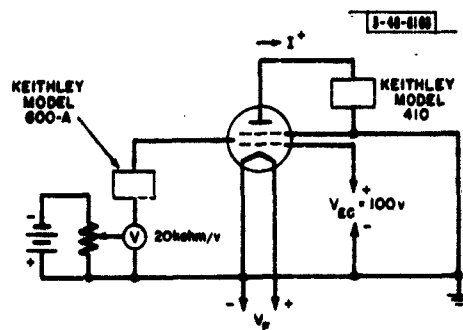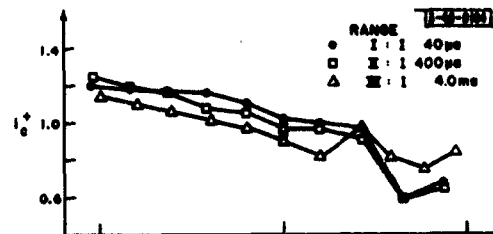
Fig. 11. Potentiometer circuit for measuring wall potentials.

TABLE V WALL POTENTIALS IN BAYARD-ALPERT AND NOTTINGHAM GAUGES AT 1.5×10^{-8} TORR				
I^-	BA		N	
	V_p (volts)	V'_p (volts)	V_p (volts)	V'_p (volts)
40 μa	−0.78	−0.81	−0.18	−0.20
400 μa	−0.83	−0.84	−0.18	−0.19
4.0 ma	−0.90	−0.92	−0.17	−0.19

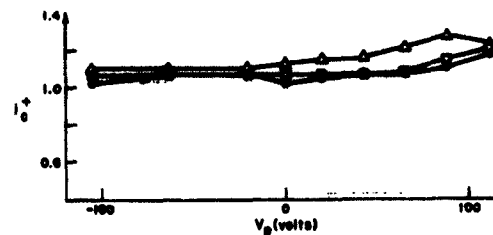

(a) Bayard-Alpert gauge.

(b) Nottingham gauge.

Fig. 12. Effect of wall potential on sensitivity.

Nottingham gauge, both with plated walls — the same two gauges mentioned above — were attached to the same vacuum system. Whichever gauge was not under test at the time served as a monitor of the pressure, which ranged from 4 to 6×10^{-8} torr during these measurements. The plating on the wall of the test gauge was connected to a voltage source, and the potential varied. For each potential (V_p), we noted I_1^+ and I_1^- for the test gauge, and I_2^+ for the monitor gauge. Both gauges were set to have I^- the same with $V_p = 0$, and then were not readjusted. The ratio of the ion currents of the two gauges, $I_1^+/I_2^+ = i^+$, is a number proportional to the sensitivity of the test gauge, so long as I_1^- is constant. At potentials greater than that of the filament, I_1^- decreases, because some of the electron emission from the filament is now going to the plating. We correct i^+ for this effect, by assuming a proportional relation between i^+ and I_1^- and calculating $i_c^+ = i^+ (I_1^-/I_0^-)$, where I_0^- is the normal value. It is this corrected value that is shown in Fig. 12(a).

In contrast with these results, we see in Fig. 12(b) the results of the same tests on the Nottingham gauge. Here we can see that the gauge sensitivity is much less affected by variations in wall potential. It was also noted that in this gauge I^- was less affected by variations in V_p than in the other gauge.

Our disagreement with Ehrlich is not explained since he measured the electron current in the same way.[13]

We have also measured wall potential during the degassing of the Nottingham gauge. Degassing is accomplished by putting about 1500 volts on both electron collector and screen, and drawing about 50 ma to each. During this time, the gauge wall charges up to nearly 1500 volts, as we found by measurement, and consistent with the work of Carter, et al.[4,5] As a consequence of the accompanying electron bombardment of the wall adjacent to the filaments, the glass can be warmed sufficiently to soften it. We have noted strain patterns in gauges which have been degassed in this manner. This effect has been cited as a reason for degassing the screen by rf induction heating. It is not always convenient to do this, however, and it need not be resorted to. The trouble is easily solved by wrapping aluminum foil about the gauge, and connecting it electrically to one of the filaments, during degassing. Gauges treated in this way have shown no strain patterns.

The effect of screen potential on the sensitivity of the Nottingham gauge has been investigated. The results are plotted in Fig. 13. At positive voltages up to $V_s = V_{ec}$ the sensitivity is essentially constant. At negative voltages the sensitivity goes up, as we have already observed in the experiment on switching the screen from filament to ground potential. Since the screen has an open structure, this may be a combination screen-and-wall effect. We have remarked earlier that in an open gauge the same variation in screen potential had no effect on the sensitivity. The sharp rise in i_c^+ where V_s exceeds V_{ec} is possibly the result of collectible ions being produced within the electron collector by electrons which, in oscillating back and forth through the screen structure, passed through the electron-collector structure in the process, although they were eventually collected by the screen. It is interesting that the uncorrected sensitivity is hardly affected by the transition through this critical voltage.

Although for the range of positive V_p shown in Fig. 12(a) the gauge sensitivity decreases, consistent with what one would expect from the work of Carter, et al.,[4,5] some measurements at higher V_p, where $V_p > V_{ec}$, show a large _increase_ in sensitivity. This is not necessarily a contradiction, however, because, as they point out, in actual operation of the gauge there is no net electron current to the wall. The electron current from wall to electron collector is the same
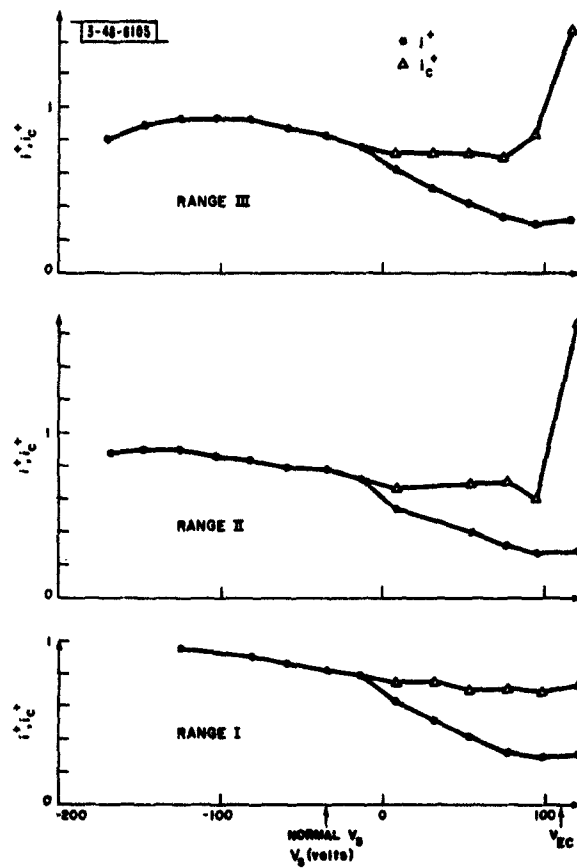
Fig. 13. Effect of screen voltage on sensitivity.

as from filament to wall. The returning electrons have low energy, and produce no ions. Since they contribute to I^-, but not to I^+, the gauge constant is smaller than it would be if no electrons went to the wall. In our measurements, the electrons going to the wall are taken out of the system, and none are returned.

Carter, et al., have also pointed out[5] that the wall-potential effect is much less likely to happen at low electron-collector voltages of the magnitude that we used than at higher voltages, above 250 volts. Also, in a well-outgassed system the effect is much less probable. This suggests that if one should use a somewhat lower electron-collector voltage than is used in most commercial gauges, he would be fairly safe from trouble with the bistable operation of the gauge. In any case, we have never observed this effect in our work.

V. SUMMARY

Our results may be summarized in several conclusions. Some of these conclusions are neither new nor surprising, but they are drawn from direct experiments rather than by inference.

(a) Whether or not the screen of the Nottingham gauge is effective depends on what effects are of concern.

> (1) The screen seems to be effective in shielding the rest of the gauge from electromagnetic disturbances.

> (2) The screen reduces or eliminates disturbances produced by positive ions from external sources.

> (3) The screen reduces electron flow to the gauge envelope, but does not prevent the envelope from eventually charging up to about the same potential as it would have in the absence of the screen.

> (4) The screen causes the gauge sensitivity to be independent of wall potential over a rather large range of the latter.

> (5) Contrary to expectations, the screen does not seem to produce any considerable increase in the sensitivity of the gauge. No increase was found in the open gauge, and about 15 percent in the enclosed gauge. It appears that the screen shields the gauge from some bad effects of the charged envelope, but does not basically improve the electron trajectories in the absence of a wall effect.

(b) We pointed out that the disadvantage of the screen is that it has to be degassed, and at the same time as the electron collector. Some accomplish this by rf induction heating of the former while electron-bombarding the latter. We have used a double-output power supply and bombarded both simultaneously, and have avoided intense electron bombardment of the glass wall by wrapping aluminum foil about the gauge during outgassing, and connecting it to the filament. This keeps the inner wall near zero potential, and results in negligible local heating of the glass walls.

(c) In a general way, it seems that the Nottingham gauge is less sensitive to irrelevant aspects of its environment.

> (1) It is shielded by the screen, as stated in (a(1)) and (a(2)).

> (2) Since the screen reduces electron flow to the envelope (a(3)), one would expect a reduction in pumping and outgassing at the walls. Whatever the specific mechanism responsible, this expectation seems to be borne out by the more consistent agreement between the two Nottingham gauges than between the Bayard-Alpert gauges. Contradicting this general conclusion is the systematic, and rather large drop in relative sensitivity of N1 with respect to N2 at high pressures on range III. This same drop does not appear in comparing BA1 with BA2.

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(d) Except for the effects noted in (a(1)) and (a(2)), there is no choice between the Nottingham and Bayard-Alpert gauges of the open variety.

(e) In view of our difficulties with an apparently well-outgassed system, which were detected only because of our system of checking, it is desirable that outgassing and processing techniques be scrutinized carefully for effects which might go undetected with a single gauge.

(f) Certain effects arising from interactions between gauges can be detected by a gauge if it is operated by a power supply in which the emission current is stabilized, but the collected electron current is indicated, although the effects in question may be too rare to justify the expedient. In any case, the placing of the electron-current meter next to the electron collector rather than the filament seems well justified on the grounds that the collected current is more significant than the emitted current.

(g) Normal errors arising from the pumping action of the gauges, and even the more drastic Blears effect arising from operation of the gauge in the presence of oil vapors, can be avoided easily. First, our results confirm the desirability of operating the gauge at low electron current. In addition, our work has shown that the Blears effect is negligible, even with an enclosed gauge, if a connecting tube of reasonable conductance is used. The connecting tube used in our case was not selected with any particular forethought beyond that of convenience, and what seemed like a "good" design. The dimensions are not outlandish, although they are notably better than those for some commercial gauges, and in many vacuum systems could be used quite readily. It does not seem unreasonable to suggest that more of the commercial gauges be supplied with tubing of a size comparable with ours.

(h) We also recommend the use of an electron-collector potential around 100 volts, or so, to avoid bistable operation.

(i) Although we did not calibrate the Redhead gauge against a standard, our results lead us to believe that it is linear in the range in which we operated. It is troubled with a jittery behavior, and, in a small range in the low 10^{-9}-torr region, a rather large jump in sensitivity as it switches into a different mode of operation. We have noted the larger scatter of its readings, relative to those of ionization gauges. The inaccessibility of the interior to rf induction heating is a drawback.

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APPENDIX
THE IONIZATION GAUGE POWER SUPPLY

Commercial power supplies for ionization gauges give insufficient information to the investigator of these gauges, and provide insufficient flexibility of operation. We have designed a power supply with the following properties of interest to us:

(1) The electron current can be stabilized to any one of three values, nominally 4 ma, 400 and 40 μa, available in a selector switch,

(2) A "standby" circuit which allows the filament to run at operating temperature while the accelerating voltage is off,

(3) Provision for turning off the filament while the electrode voltages stay on,

(4) A meter to monitor filament voltage.

The standby setting allows one to turn the gauge on and off without introducing the gas burst from the filament at turn-on. The third provision allows a check of the ion-collector current, to see how much, if any, is leakage from other electrodes. The filament meter is included, because it has been found that the filament itself is a fairly sensitive indicator of changes in vacuum conditions, as was mentioned earlier.

The power supply (Fig. A-1) consists of a filtered dc source, with two shunt regulators arranged to provide +135 volts to the electron collector and +30 volts to one side of the filament. This permits the screen to be grounded and the ion collector to return to ground through the electrometer.
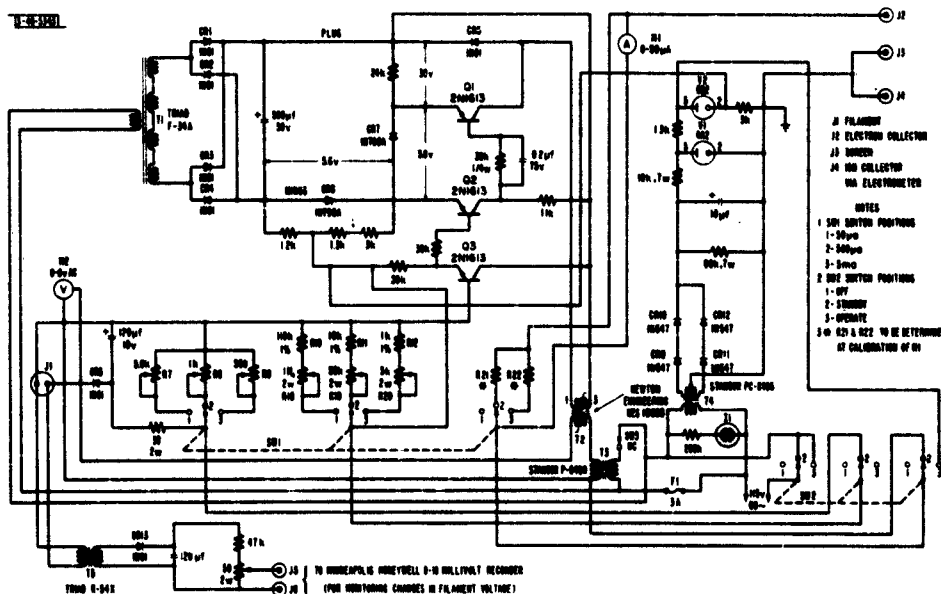

Fig. A-1. Schematic of the ionization gauge power supply.

The electron-collector current is monitored, and the monitor automatically adjusts the filament power to maintain the electron-collector current constant to any value determined by the operator. The automatic control operates in the following manner. The electron-collector current flows through R_{10}, R_{11}, or R_{12}, depending on the current range chosen. The resultant voltage drop is the base voltage of the emitter follower Q_3. The emitter voltage of Q_3 is compared with a Zener reference voltage. A voltage in excess of the Zener voltage produces a base current flow in Q_2 which is amplified in Q_2 and Q_4. The circuit is arranged so that an increasing current in Q_2 causes a decreasing current to flow in Q_4. The current flowing in Q_4 flows through the control winding of a saturable reactor whose gate windings are in series with the filament supply of the vacuum gauge. The gate winding reactance is maximum when the control current is zero. The control loop is thus closed by the saturable reactor.

When in the standby mode, a dc voltage proportional to the filament ac voltage is compared with the Zener reference voltage, and regulation of the filament voltage in the absence of electron-collector current is achieved through the same chain of events described above.

ACKNOWLEDGMENT

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ADDENDA
for
Technical Report No. 298

SOME TESTS OF IONIZATION GAUGES
F. T. Worrell

During a further examination of some of the effects described in TR-298, the author has discovered some errors in Figs. 4 and 7. Corrected versions of these figures are reproduced herein. In Figs. 4(a) and (b) a point near the bottom of the graph is now at the top, and some points previously omitted from the prints have been inserted. In Figs. 7(a-c) points inadvertently omitted have been put in, while plotting errors have been corrected in 7(a) and (c). The result of the first change is to bring three related points into a more consistent relationship with one another on all the graphs. These points are enclosed by a curved line in each graph in Figs. 4 and 7. It is now possible to explain tentatively a scatter that was previously unexplainable.

The footnote on page 12 may still be valid, but it should be changed to say that _in all cases_ (omitting "but one") the notably erratic K_o-values were high, since the point that has been corrected was previousl, the exception. However, another explanation for the scatter suggests itself, and may replace the discussion in the first paragraph on page 12. If we consider the three troublesome points, we note that, in Fig. 4, the scatter is worst for BA2, almost as bad for N2, less for BA1, and barely noticeable for N1. The relative order in which these effects occur, and the direction of the deviations from the norm are consistent with the Redhead gauge interaction discussed on pages 13−17. Unfortunately, there is no record of disturbances in I^- having been noted at these times, so the explanation is speculative.
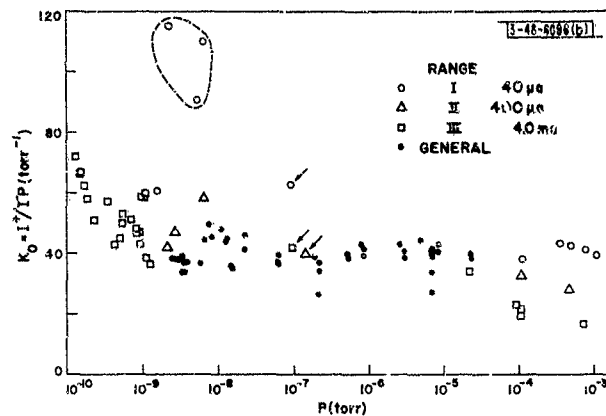
In view of this plausible explanation, the removal of these points on the grounds that they are not representative of normal behavior seems justified. If this is done, it will be seen that the remaining plots in Fig. 4, and more especially Fig. 7, are notably improved. In particular, the agreement between N2 and BA2 in Fig. 7(d) is now very good.
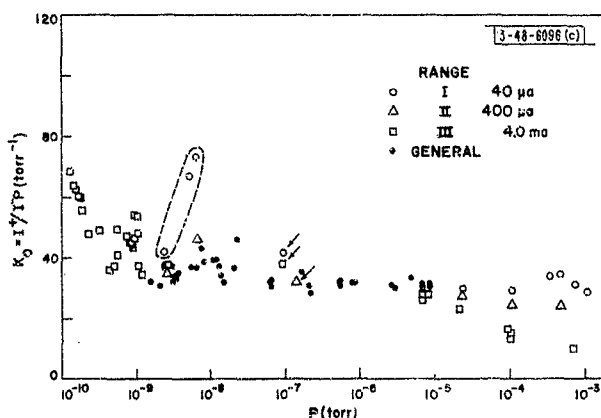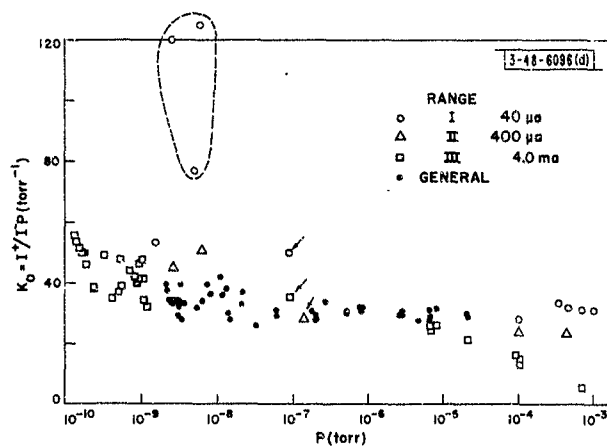
14 May 1963

A-1

(a) The enclosed Nottingham gauge, N1.
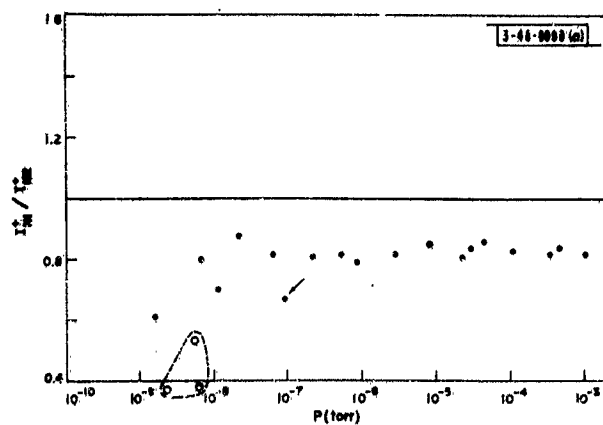

(b) The open Nottingham gauge, N2.

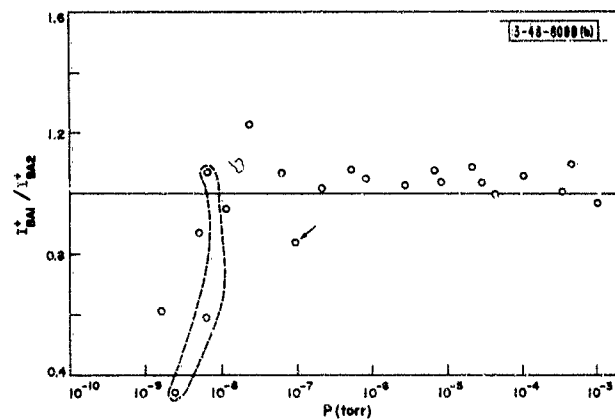(c) The enclosed Bayard-Alpert gauge, BA1.

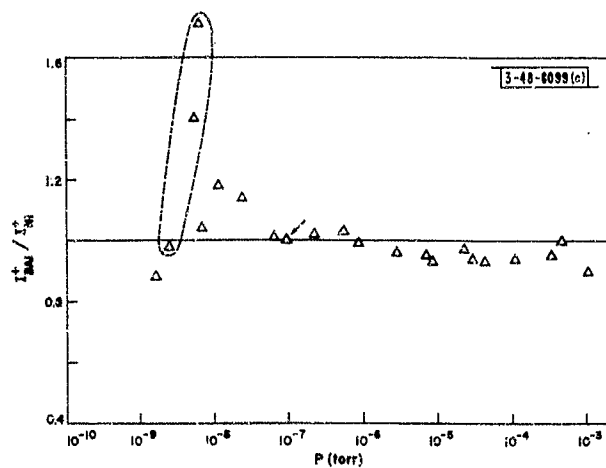(d) The open Bayard-Alpert gauge, BA2.

Fig. 4. Sensitivity of ionization gauges at various pressures.
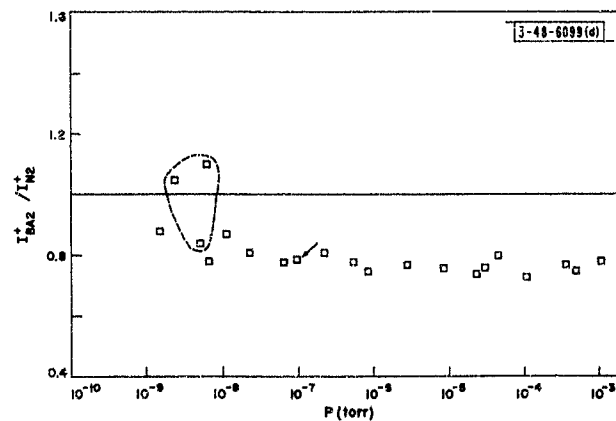
(a) The two Nottingham gauges, N1 and N2.

(b) The two Bayard-Alpert gauges, BA1 and BA2.

(c) The two enclosed gauges, BA1 and N1.

(d) The two open gauges, BA2 and N2.

Fig. 7. Comparisons of gauges in pairs, range 1 (40 µa).

A-3